

AD-A284 363



(1)

Carderock Division

Naval Surface Warfare Center

Bethesda, Md. 20084-5000

CARDIVNSWC-TR-61-CR-94/01 February 1994

Survivability, Structures, and Materials Directorate
Technical Report**Size and Deformation Limits to Maintain
Constraint in K_{IC} and J_C Testing of
Bend Specimens**

Prepared by

Kyle C. Koppenhoefer, University of Illinois

Robert H. Dodds, Jr., University of Illinois

Under Contract to:

Naval Surface Warfare Center

Annapolis Detachment, Carderock Division

Code 614

Annapolis, MD 21402-5067

Prepared for

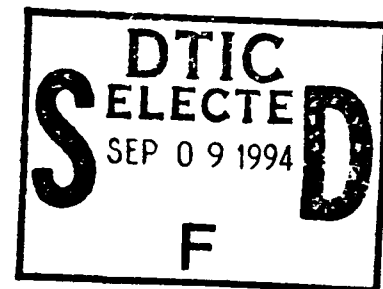
Division of Engineering

Office of Nuclear Regulatory Research

U.S. Nuclear Regulatory Commission

Washington, D.C. 20555

NRC FIN J6036



268

94-29373



DTIC QUALITY ASSURED



Approved for public release; distribution is unlimited.

94 0 07 1 7 7

Size and Deformation Limits to Maintain Constraint in K_{Ic} and J_c Testing of Bend Specimens

By

Kyle C. Koppenhoefer

*Department of Civil Engineering
University of Illinois*

Robert H. Dodds, Jr.

*Department of Civil Engineering
University of Illinois*

Mark T. Kirk

Edision Welding Institute

A Report on a Research Project Sponsored by the:
**Annapolis Detachment, Carderock Division
Naval Surface Warfare Center
CDNSWC 614
Annapolis, Maryland 21402-5067**

DTIC QUALITY INSURED **3**

**University of Illinois
Urbana, Illinois
January 1994**

ABSTRACT

The ASTM Standard Test Method for *Plane-Strain Fracture Toughness of Metallic Materials* (E399-83) restricts test specimen dimensions to insure the measurement of highly constrained fracture toughness values (K_{Ic}). These requirements insure small-scale yielding conditions at fracture, and thereby the validity of linear elastic fracture mechanics. When these conditions are satisfied, the diameter of the plastic zone is nearly twenty five times smaller than all specimen dimensions. The need for this degree of plastic zone confinement, set by the factor 2.5 in $a, b, B \geq 2.5(K_q/\sigma_{ys})^2$, was based on K_{Ic} data for many different alloys. These data show that all specimens satisfying the size requirements of E399 produce highly constrained fracture toughness values. However, the required multiplier ranges from 1.0 for certain steel alloys to 2.5 for titanium alloy 6-6-2 in the aged condition. To maintain a standard test method applicable to all materials, the more restrictive 2.5 value has been retained by ASTM Committee E08.

Recently, Dodds and Anderson have proposed a less restrictive size requirement for cleavage fracture toughness measured in terms of the J -integral (J_c). Dodds and Anderson performed finite element analyses to calculate the ratio of J in the finite-sized specimen ($J_{SE(B)}$) to J under small-scale yielding (J_{SSY}) needed to produce equivalent stresses ahead of both crack tips, and thereby equivalent conditions for cleavage fracture. The proposed size requirement specifies the deformation level at which $J_{SE(B)}/J_{SSY}$ deviates from unity for deeply cracked bend specimens, and is given by $a, b, B \geq 200 J_c/\sigma_0$.

The size requirement proposed by Dodds and Anderson increases the utility of fracture toughness experiments by expanding the range of conditions over which such data can be reliably measured. This investigation compares the proposed size requirement with that of ASTM Standard Test Method E399 and, by comparison with published experimental data, provides validation of the new requirements.

Accession For	
NTIS CRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
A-1	

ADMINISTRATIVE INFORMATION

The work reported herein was funded under the Elastic-Plastic Fracture Mechanics of LWR Alloys Program at the Annapolis Detachment, Carderock Division, Naval Surface Warfare Center, Contract Number N00167-92-K-0038. The Program is funded by the U.S. Nuclear Regulatory Commission (USNRC) under Interagency Agreement RES-93-002. The Technical Program monitor is Dr. S. N. Malik at the USNRC. Technical monitoring of the contract was performed by Dr. Richard E. Link (CDNSWC 614).

Contents

Section No.	Page
Abstract	ii
Administrative Information	iii
List of Figures	v
List of Tables	vi
Acknowledgements	vii
1. NOMENCLATURE	1
2. INTRODUCTION	1
3. THEORETICAL BACKGROUND	2
3.1 Dodds-Anderson micromechanics model	2
3.2 J - Q theory	4
3.3 Statistical thickness effects	6
4. EVALUATION OF SIZE REQUIREMENTS	7
4.1 Materials and basis of comparison	7
4.2 Experimental data	7
5. SUMMARY AND DISCUSSION	12
6. REFERENCES	14

LIST OF FIGURES

Figure No.		Page
1	Areas within principal stress contours for an $a/W = 0.15$, $n=10$ SE(B). Values are normalized by area within contour for SSY at same J -value	3
2	Variation of finite body-to-SSY J with applied load for various strain hardening exponents in an $a/W = 0.5$ SE(B) specimen	4
3	Variation of Q with applied load for an $a/W = 0.5$ SE(B)	5
4	Variation of fracture toughness with specimen thickness for A36 steel at -76°C	8
5	Variation of fracture toughness with crack depth for A36 steel at -76°C	9
6	Variation of fracture toughness with specimen thickness for A533-B at -75°C	10
7	Variation of fracture toughness with thickness for 18 Ni maraging steel	10
8	Variation of fracture toughness with specimen thickness for 4340 steel $a_0 = 28$ mm, $W = 56$ mm	11
9	Variation of fracture toughness with specimen thickness for 4340 steel $a_0 = 12.7$ mm, $W = 25.4$ mm	11
10	Variation of fracture toughness with specimen thickness for 4340 steel, $a_0 = 6.9$ mm, $W = 14$ mm	12
11	Variation of fracture toughness with thickness for Ti 6Al-6V-2Sn	13

LIST OF TABLES

Table No.	Page
1 References for Experimental Data	6
2 Material properties and size ratios for experimental data	7

ACKNOWLEDGEMENTS

This investigation was supported by grants principally from the Nuclear Regulatory Commission with additional support from Code 2814, Annapolis Detachment, Carderock Division of the Naval Surface Warfare Center.

The authors wish to acknowledge the many useful discussions with Dr. Kim Wallin of the Technical Research Center of Finland.

1. NOMENCLATURE

a	crack length, mm
b	length of uncracked ligament, mm
B	specimen thickness, mm
B_0	normalizing thickness, mm
σ_{ys}	yield strength, MPa
σ_{uts}	ultimate tensile strength, MPa
σ_0	flow strength (average of yield and ultimate strength), MPa
E	Young's modulus, MPa
ν	Poisson's ratio
r, θ	polar coordinates from crack tip
T	stress parallel to the crack, MPa
δ_{ij}	Kronecker delta
Q	higher order term of an asymptotic series
K_{corr}	fracture toughness corrected for statistical thickness effects, $\text{MPa}\sqrt{\text{m}}$
K_{min}	threshold fracture toughness, $\text{MPa}\sqrt{\text{m}}$
K_I	experimental fracture toughness, $\text{MPa}\sqrt{\text{m}}$
K_q	provisional fracture toughness value, $\text{MPa}\sqrt{\text{m}}$

2. INTRODUCTION

The ASTM Standard Test Method for *Plane-Strain Fracture Toughness of Metallic Materials* (E399-83) restricts specimen dimensions relative to the deformation at fracture to insure that measured fracture toughness values (K_{Ic}) correspond to highly constrained crack-tip conditions. These requirements are as follows:

$$a, b, B \geq 2.5 \left(\frac{K_q}{\sigma_{ys}} \right)^2 \quad (1)$$

Satisfaction of Eq (1) insures small-scale yielding conditions at fracture, and thereby validates the assumptions of linear elastic fracture mechanics. The approximate diameter of the plastic zone under conditions given by Eq (1),

$$d_p \geq \frac{1}{3\pi} \left(\frac{K_q}{\sigma_{ys}} \right)^2 \quad (2)$$

is nearly 25 times smaller than relevant specimen dimensions. This degree of plastic zone confinement, set by the 2.5 multiplier in Eq (1), is based on experimental K_{Ic} data for many different metals. These data confirm that specimens satisfying Eq (1) produce equivalent (within scatter) fracture toughness values. However, different materials do not all indicate the need for a multiplier as severe as 2.5. Rolfe and Novak[15] and Facuher and Tyson [5] found that the 2.5 value could be reduced to as low as 1.0 for certain steel alloys (e.g. 18 Ni Maraging steel, micro-alloyed Lloyds LT-60). In contrast, Jones and Brown [7] presented data on titanium alloy 6-6-2 in the aged condition demonstrating the need for the 2.5 value. To maintain a test stan-

dard independent of specific material, ASTM Committee E08 retains the more restrictive 2.5 value.

Recently, Dodds and Anderson [1] (hereafter referred to as DA) have proposed an alternative size requirement for cleavage fracture toughness measured in terms of the J -integral (J_c) which is less restrictive than the E399 requirement in many cases:

$$a, b, B \geq \frac{200 J_c}{\sigma_0} \quad (3)$$

This requirement derives from current research [4,6,12] examining the effects of constraint on fracture toughness. Experimental verification of Eq (3) would increase the utility of measured fracture toughness values. For most metals, valid fracture toughness values can be obtained with smaller specimens. This paper re-examines the key data sets used to set the original 2.5 factor in the E399 requirement. By using J_c , rather than K_{Ic} , as the measure of fracture toughness, the widely varying ratio of Young's modulus to yield strength is reflected in the requirements. For high strength-low modulus metals (e.g. titanium) Eq (1) and (3) are nearly identical. However, for lower strength-high modulus metals (e.g. structural steels), Eq (3) more closely agrees with the 1.0 multiplier in Eq (1). The comparisons here demonstrate that Eq (1) maintains the strict requirement of the E399 expression for materials originally used to set the 2.5 factor while correctly relaxing the size requirement for other metals, most notably structural and pressure vessel ferritic steels.

3. THEORETICAL BACKGROUND

Much recent work [4,13,17] in fracture mechanics focuses on quantifying the kinematic constraint against plastic flow at the crack tip to predict the effects of finite component size on fracture toughness. Two approaches of particular interest are the DA micromechanics constraint model, and the J - Q theory to describe crack tip fields as developed by O'Dowd and Shih [12,13]. These approaches determine the level of loading, relative to specimen size, when global plasticity impinges on the small scale yielding (SSY) crack tip fields. Once global plasticity affects the near tip fields, the unique coupling between J , K_I and the near tip fields is lost and specimen size (and geometry) influences the measured fracture toughness. The size requirements given in Eq (1) were first proposed by DA and, as will be shown here, are corroborated by the J - Q methodology.

3.1 Dodds-Anderson Micromechanics Model

DA quantify the geometric effects on fracture toughness by coupling the global failure parameter (J_c) with a micromechanics based failure model. The model is designed for ferritic materials in the ductile to brittle transition region thereby limiting the fracture mechanism to transgranular cleavage. For this failure mechanism, several micromechanical models have been recently proposed [2, 9]. These models assume a favorably oriented particle (e.g. carbide or inclusion) initiates cleavage fracture. Failure of this particle creates a microcrack which triggers global fracture through a local Griffith instability. The sampling effects for a favorably oriented particle to create the initial microcrack suggests that the highly stressed volume of material ahead of the crack plays a dominant role. These features lead to adoption of the volume of material ahead of the crack over which the normalized principal stress (σ_1 / σ_0) exceeds a critical value as the local failure parameter. In plane-strain, the volume is simply the area (4) within a contour \times the thickness (B). Dimensional analysis [1] demonstrates that

$$A(\sigma_1/\sigma_0) \propto \frac{J^2}{\sigma_0^2} \quad (4)$$

DA use nonlinear finite element analyses of plane strain models to calculate areas within principal stress contours ahead of a crack tip. The analyses reveal that as deformation applied to a single edge notch bend (SE(B)) specimen increases, the area within a stress contour ahead of the crack tip increases but at a slower rate (due to constraint loss) than the small-scale yielding (SSY) limit (Fig. 1). As is ap-

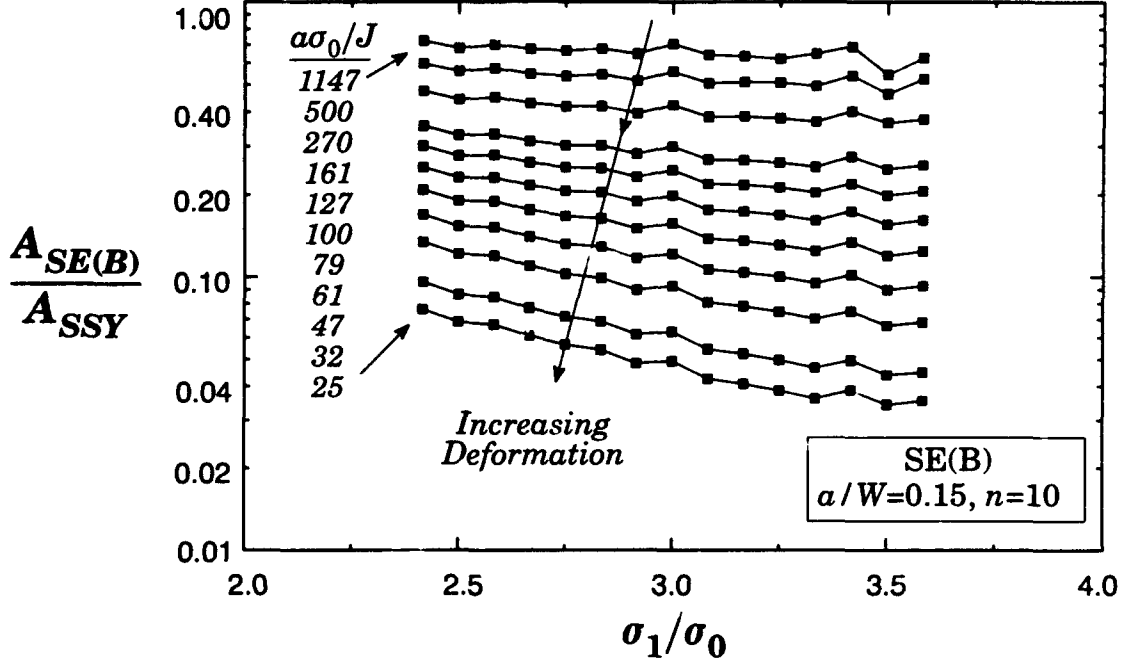


FIG. 1—Areas within principal stress contours for an $a/W = 0.15$, $n=10$ SE(B). Values are normalized by area within contour for SSY at same J -values.

parent from the nearly horizontal lines in Figure 1, the level of deviation from SSY is essentially independent of the critical principal stress contour until large amounts of deformation. These analyses define deformation levels beyond which specimen dimensions influence the relationship between applied- J and area within a principal stress contour which drives the cleavage fracture (i.e. the measured J_c values become a function of specimen geometry). The area ratio is recast in terms of J as,

$$\frac{J_{SE(B)}}{J_{SSY}} = \sqrt{\frac{A_{SSY}}{A_{SE(B)}}} \quad (5)$$

DA calculate the ratio of J in the finite size specimen ($J_{SE(B)}$) to the J under small-scale yielding conditions (J_{SSY}) which generates equivalent stressed areas in the SE(B) and SSY conditions. The ratio $J_{SE(B)}/J_{SSY}$ quantifies the deviation from SSY conditions. Figure 2 shows the variation of this ratio with applied load and strain hardening exponent and illustrates the basis for the size requirement on in-plane dimensions (a and b) expressed by Eq (3). At low deformation levels, plasticity in the SE(B) specimen is well contained (i.e. small scale yielding); increases of $J_{SE(B)}$ generate the same stressed volume of material as in SSY. As deformation increases, global plasticity affects the near tip stresses, and $A_{SE(B)}$ increases at a substantially slower rate than A_{SSY} . As is apparent from Figure 2, the ratio $J_{SE(B)}/J_{SSY}$ begins

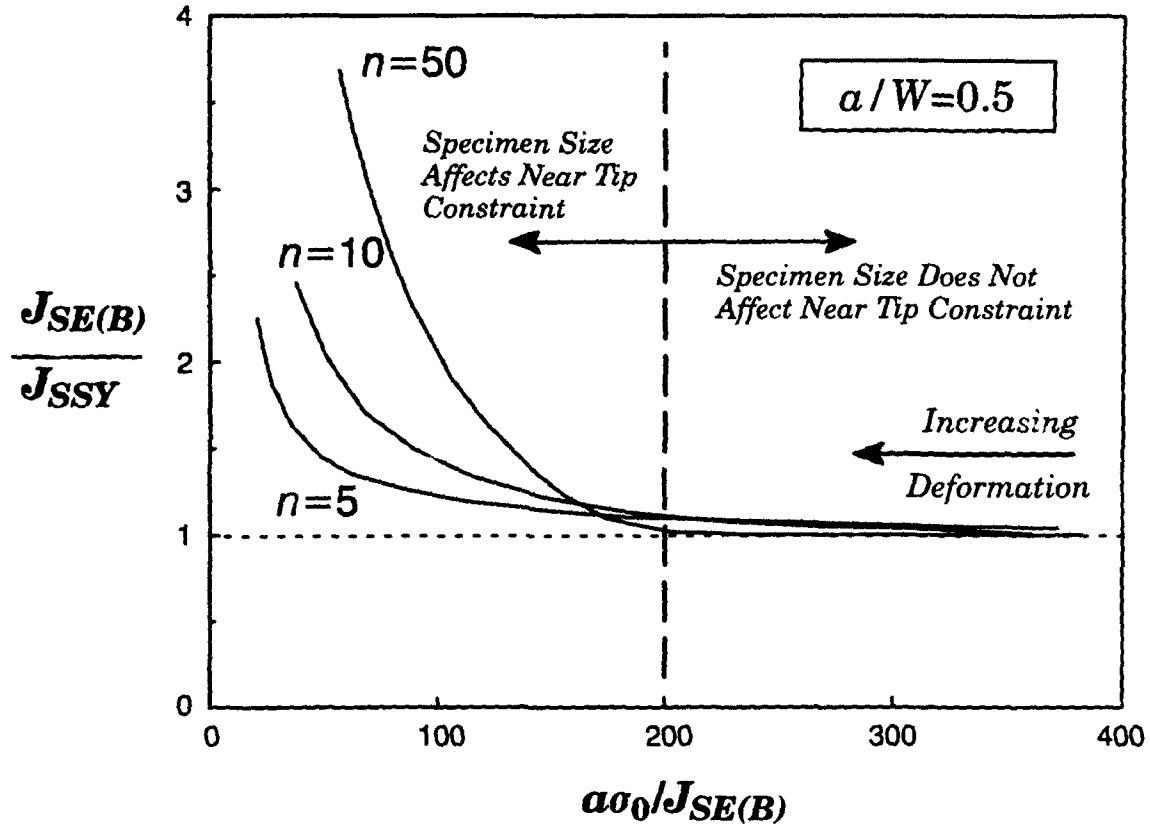


FIG. 2—Variation of finite body-to-SSY J with applied load for various strain hardening exponents in an $a/W = 0.5$ SE(B) specimen.

to increase rapidly above unity at a non-dimensional deformation of 200. The crack length provides a meaningful length to scale the level of plastic deformation relative to the in-plane size of the specimen. 3D finite element analyses of SE(B) specimens by Narasimhan and Rosakas [11], and preliminary work by Dodds [3], indicate that thicknesses, B , satisfying Eq (3) also maintain SSY conditions.

3.2 J - Q Theory

The J - Q description of crack tip fields evolves from consideration of the Modified Boundary Layer (MBL) solution [20] which expresses near tip stresses for linear elastic plane strain conditions in the form,

$$\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}} \tilde{f}_{ij}(\theta) + T\delta_{1i}\delta_{1j} \quad (6)$$

where T is the non-singular stress parallel to the crack plane. The T -stress term does not affect K_I or J ; however, Larsson and Carlsson [8] demonstrate the second term significantly affects the plastic zone shape and size under SSY conditions. In finite-sized specimens the elastic T -stress, which varies proportionally with K_I , becomes ambiguous under conditions of large scale yielding as K_I saturates to a constant value at limit load.

O'Dowd and Shih use asymptotic and finite element analyses to develop an approximate two-parameter description of the crack tip fields without the limitations of the T -stress,

$$\sigma_{ij} = \sigma_0 f_{ij}\left(\frac{r}{J/\sigma_0}, \theta; Q\right), \quad (7)$$

$$\varepsilon_{ij} = \varepsilon_0 g_{ij}\left(\frac{r}{J/\sigma_0}, \theta; Q\right). \quad (8)$$

The second term, Q , in Eqs (7,8) is the mechanism by which σ_{ij} and ε_{ij} of an SE(B) differ from the SSY solution at the same applied- J . O'Dowd and Shih determined that, to a good approximation, Q represents a uniform hydrostatic stress in the forward sector ahead of the crack tip, $|\theta| < \pi/2$ and $J/\sigma_0 < r < 5J/\sigma_0$. Operationally, Q is defined as

$$Q \equiv \frac{(\sigma_{\theta\theta})_{SE(B)} - (\sigma_{\theta\theta})_{SSY}}{\sigma_0}, \quad \text{at } \theta = 0, r = 2J/\sigma_0 \quad (9)$$

where stresses in Eq (9) are evaluated from plane strain finite element analyses containing sufficient mesh refinement to resolve the fields within the process zone for ductile and brittle fracture. At low deformation levels, the finite body is under SSY conditions and Q remains very nearly zero; however, under large-scale yielding conditions stresses at the crack tip are substantially less than those in SSY at the same J -values. This difference leads to negative Q values once the SE(B) specimen deviates from SSY conditions (Fig. 3). For deep notch bend specimens Q remains slightly positive at deformation corresponding to $a\sigma_0/J_c > 200$.

The J - Q description of crack-tip stress and strain fields expressed in Eqs (7,8) provides the needed justification to apply the requirements of Eq (3) to materials

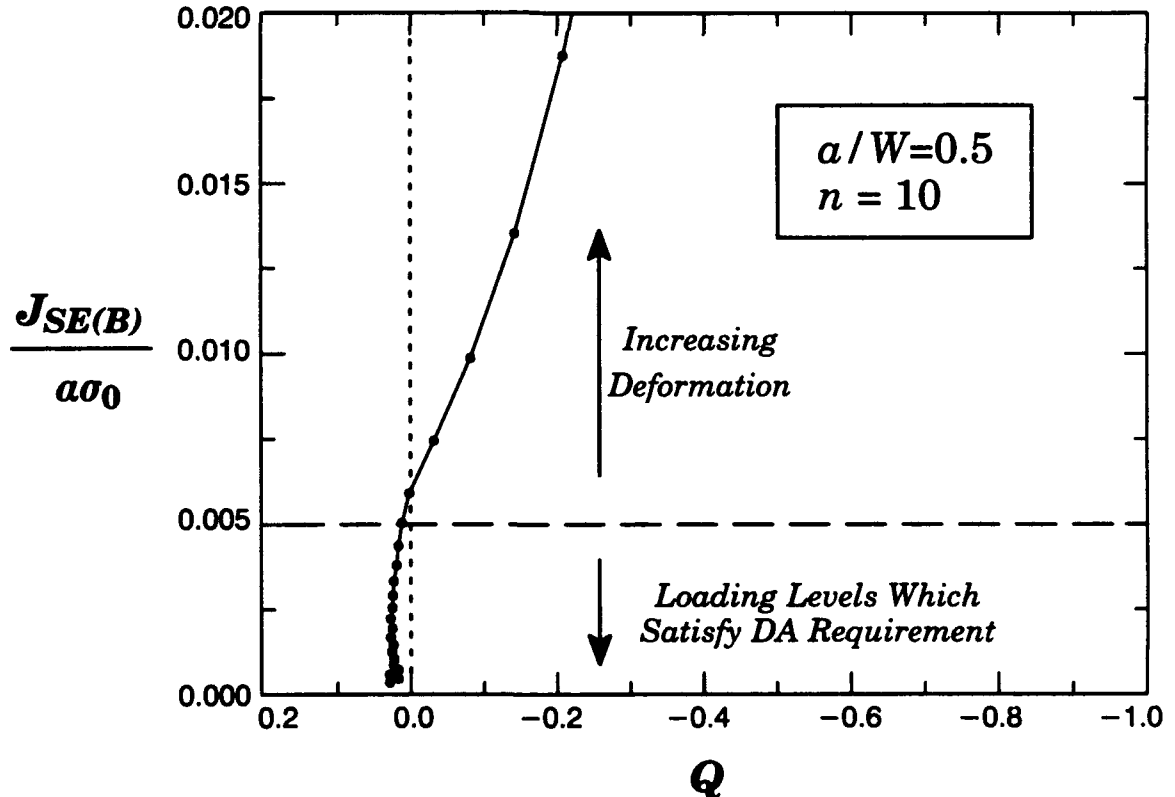


FIG 3.—Variation of Q with applied load for an $a/W=0.5$ SE(B).

that do not necessarily fracture by the purely stressed controlled, transgranular cleavage mechanism of the DA model. Satisfaction of the size-deformation requirements in Eq (3) insures that both the stress and strain fields at fracture correspond to SSY and are unaffected by the global response of the specimen. Consequently, the specific details of the fracture micromechanism (stress vs. strain controlled) become unimportant since J (or K_I) uniquely defines both fields.

3.3 Statistical Thickness Effects

Previous experimental and theoretical work [18,19] on ferritic steels demonstrates an absolute thickness effect on fracture toughness not related to constraint. Metallurgical variations in the material along the crack front require a statistical treatment of thickness in experimental fracture toughness data. Wallin [19] employs weakest link statistics to obtain the following statistical correction for fracture toughness data of specimens of different thickness (B and B_0) which fail by cleavage without previous ductile tearing,

$$K_{\text{corr}} = K_{\text{min}} + (K_{Ic} - K_{\text{min}}) \left(\frac{B}{B_0} \right)^{1/4} \quad (10)$$

Recasting Eq (10) in terms of J yields,

$$J_{\text{corr}} = J_{\text{min}} + (J_c - J_{\text{min}}) \left(\frac{B}{B_0} \right)^{1/2} \quad (11)$$

The corrections given in Eqs (10,11) arise solely from the increased volume of material sampled along the crack front due to increased thickness. Each point along the crack front is *assumed* to be stressed at the same level. J_{min} for ferritic materials is quite small and can be neglected. As the sampled volume increases, the probability of finding a metallurgical weak link increases. Because the failure of a weak metallurgical defect controls cleavage fracture, fracture toughness decreases with increasing probability of finding a defect.

The statistical assumptions employed to obtain Eqs (10,11) preclude application to materials which do not fracture by weakest link mechanisms. Consequently, the remainder of this presentation addresses only the deterministic effects of specimen size (i.e. constraint) on measured values of fracture toughness. Statistical treatment of fracture data, for example the thickness effect of sampled volume, should be applied only to data that first meet the deterministic requirements for specimen size that maintain constraint.

Table 1—References for Experimental Data

Material	Reference
4340 Steel (399°C Temper)	Jones and Brown, <i>ASTM STP 463</i> , 1970, pp 63–101
Ti 6Al–6V–2Sn	Jones and Brown, <i>ASTM STP 463</i> , 1970, pp 63–101
18Ni Maraging Steel	Rolfe and Novack, <i>ASTM STP 463</i> , 1970, pp 94
A36 Steel	Sorem, <i>et. al</i> , <i>International Journal of Fracture</i> , Vol. 47, pp. 105–126, 1991.
A533B Class 1 Steel	McCabe, <i>ASTM STP 1189</i> , 1991, pp. 80–94

4. EVALUATION OF SIZE REQUIREMENTS

4.1 Materials and basis of comparison

Five experimental data sets spanning a variety of metals are considered in the comparison. Table 1 lists the materials along with the original references for the data. To compare the current E-399 and proposed size requirements for these metals, it is necessary to express them using the same fracture toughness parameter. Equation (3) is converted into terms of K using the SSY conversion for plane strain conditions,

$$J = \frac{K^2}{E(1 - \nu^2)} \quad (12)$$

After converting Eq (3) to K and expressing σ_0 in terms of σ_{ys} and σ_{uts} , the DA size requirement is expressed as

$$L_{200} \geq \frac{400 K_q^2 (1 - \nu^2)}{E(\sigma_{ys} + \sigma_{uts})} \quad (13)$$

L_{200} refers to the minimum specimen size (i.e. a, b, B). With both size requirements expressed using the same fracture toughness parameter, their ratio becomes a function of material properties,

$$\frac{L_{200}}{L_{E399}} = \frac{160 (1 - \nu^2) \sigma_{ys}^2}{E (\sigma_{ys} + \sigma_{uts})} \quad (14)$$

This ratio quantifies the change in minimum specimen size afforded by the proposed size requirement for a specific material. A value of L_{200} / L_{E399} less than unity indicates that the proposed size requirement is less restrictive than the current E399 requirement. Table 2 lists, in ascending order, this size ratio for the five metals. The decrease in specimen size requirement ranges from a factor of 16 for A36 steel to 1.4 for Ti 6-6-2. The proposed size requirement is less restrictive than the E399 for all metals considered in Table 1, but only slightly so for the titanium alloy.

Table 2—Material properties and size ratios for experimental data

Material	Yield [MPa]	Ultimate [MPa]	Modulus [GPa]	Poisson's ratio	$L_{200} /$ L_{E399}
A36 Steel	248	460	207	0.3	0.06
A533B Class 1 Steel	407	559	207	0.3	0.12
18Ni Maraging Steel	1323	1379	207	0.3	0.46
4340 Steel (399°C Temper)	1468	1538	207	0.3	0.49
Ti 6Al-6V-2Sn	1200	1269	117	0.32	0.71

4.2 Experimental data

The five experimental data sets are examined in the order given in Table 2. Fracture toughness is plotted against the relevant specimen dimension. Two lines designated L_{200} and L_{E399} appear on each plot and represent the size requirements for E399 (solid line) and DA (dashed line). Fracture toughness values falling below the line satisfy the indicated size requirement.

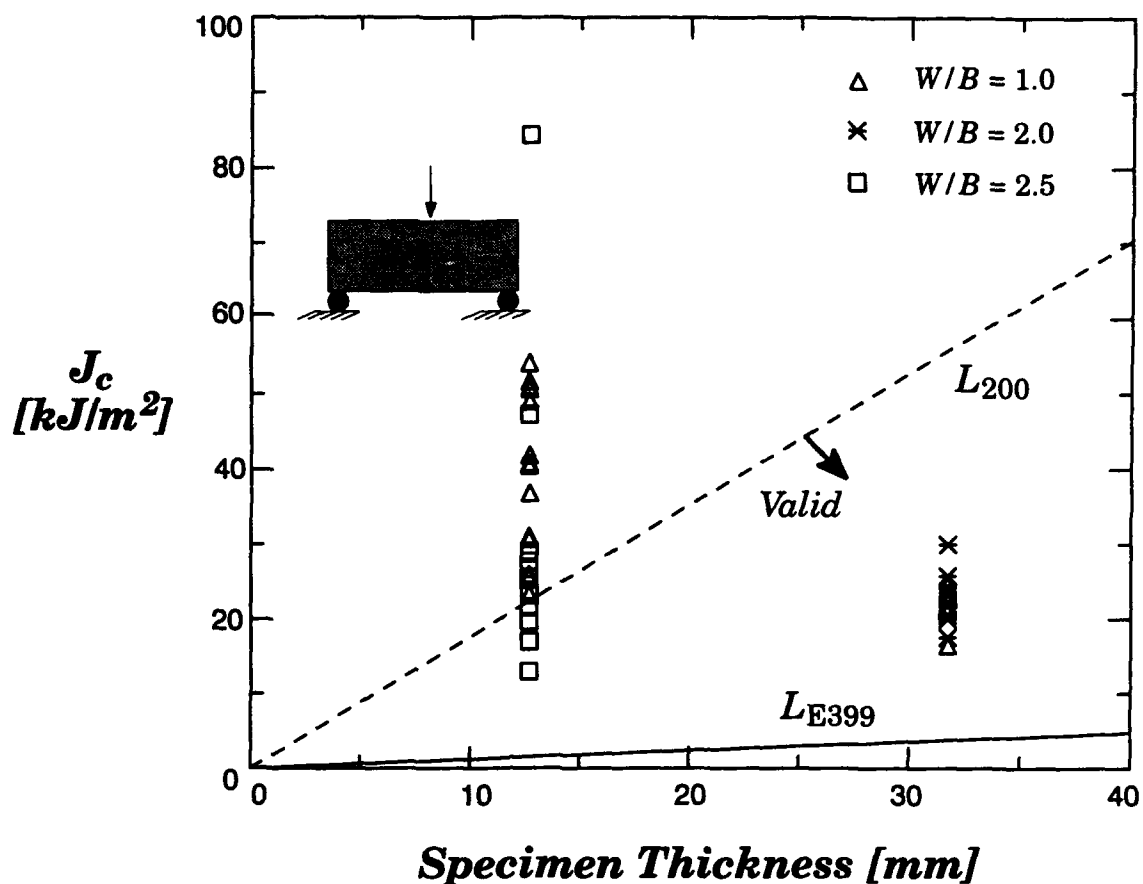


FIG. 4—Variation of fracture toughness with specimen thickness for A36 steel at -76°C .

The A36 data set consists of SE(B) specimens with a variety of crack depth, thickness, and width-to-thickness (W/B) ratios tested at -76°C . The J at cleavage, J_c , is given for two thickness ($B = 12.7$ and 31.75 mm). This data appears in Figure 4. Both thicknesses contain specimens with three different W/B ratios as indicated by the different symbols. This material provides the largest difference between L_{E399} and L_{200} ; application of the E399 size requirement eliminates the entire data set. All of the $B = 31.75$ mm data and several of the data points with $B = 12.7$ mm meet the proposed size requirement of DA. The total data set shows a significant increase in toughness with decreasing thickness; however, the L_{200} criterion eliminates data points which show an increase in fracture toughness due to large scale yielding effects. Figure 5 shows the variation of fracture toughness with crack depth for the same data set. The proposed size criterion removes J_c values dependent on crack depth while retaining significantly more data than the E399 requirement.

Figure 6 shows fracture toughness values for an A533B Class 1 steel. The data includes 1/2T, 1T, 2T and 4T C(T) specimens tested at -75°C . For this data set, the fracture toughness is plotted using K_{Jc} values obtained by converting measured J_c values using Eq (12). The proposed size requirement removes data points which otherwise cause the data set to show an increase in fracture toughness with decreasing thickness.

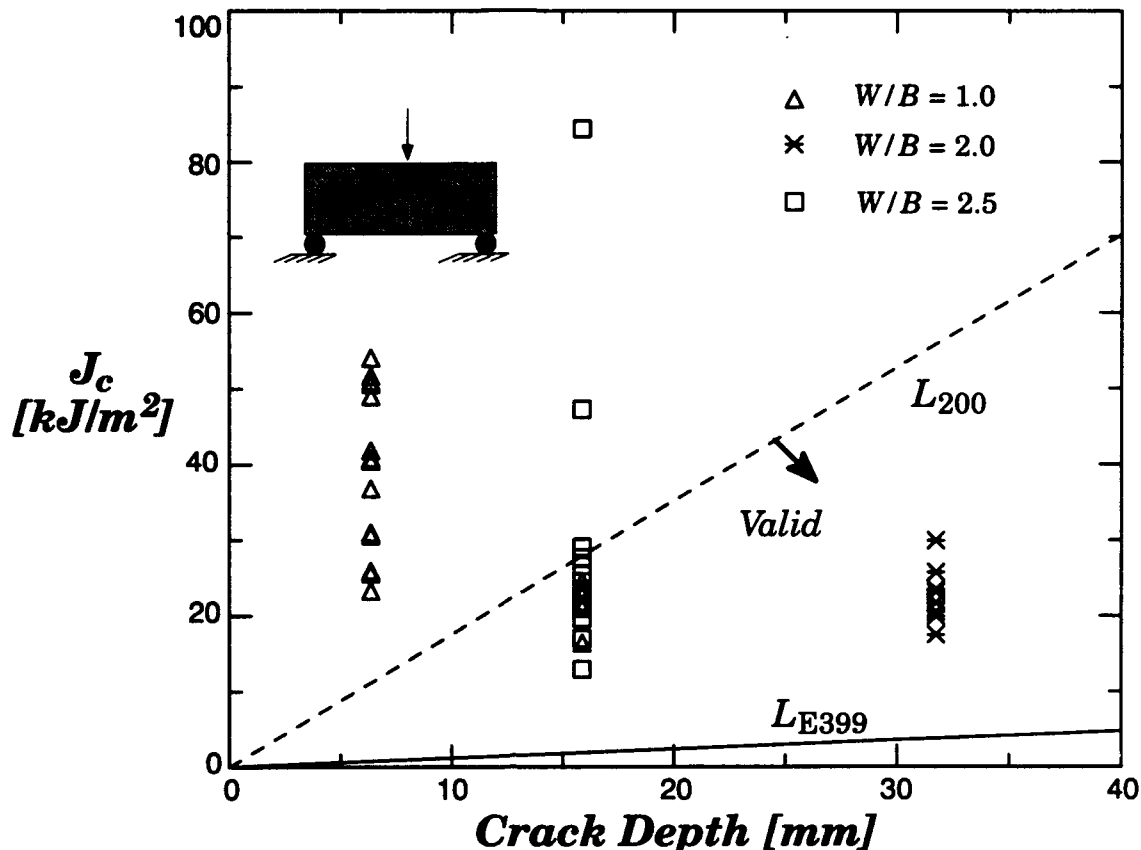


FIG. 5—Variation of fracture toughness with crack depth for A36 steel at -76°C .

Deep notch SE(B) specimens of two thicknesses ($W = 102$ and 152 mm) provide fracture toughness data for 18 Ni maraging steel (Fig. 7). Rolfe and Novak use this data to argue for a reduction of the multiplier in E399 from 2.5 to 1.0. Fracture toughness values are clearly specimen size independent for thickness greater than approximately $B = 10$ mm. The thickness requirement given by the L_{200} curve agrees with the recommendations of Rolfe and Novak.

Fracture toughness values for a 4340 steel shown in Figures 8, 9 and 10 were obtained from a series of tests conducted on specimens removed from a 25.4 mm thick, hot-rolled and annealed plate. The specimen blanks were heat treated in a neutral salt bath at 843°C for 1/2 hour, oil quenched, and tempered at 399°C for one hour. The SE(B) specimens comprised three different widths ($W = 56$, 25.4, and 14 mm) each having initial $a/W = 0.5$. Only the $W = 14$ mm data set reveals significant variations in K_Q with thickness (Fig. 10). The rapid decrease in toughness with decreasing thickness which is observed in this data set may be due to the very thin specimens (e.g. $B = 3.8$ mm). Once the specimen thickness decreases beyond a critical point, fracture toughness decreases due to the reduction of material available for plastic energy dissipation. The DA size requirement eliminates all data points showing this effect while including more, seemingly relevant data than the E399 requirement.

The high yield strength coupled with the low value of Young's modulus for Ti 6Al-6V-2Sn causes the L_{200}/L_{E399} ratio to be significantly nearer to unity for this material than for the other four materials listed in Table 1. The titanium data (Fig.

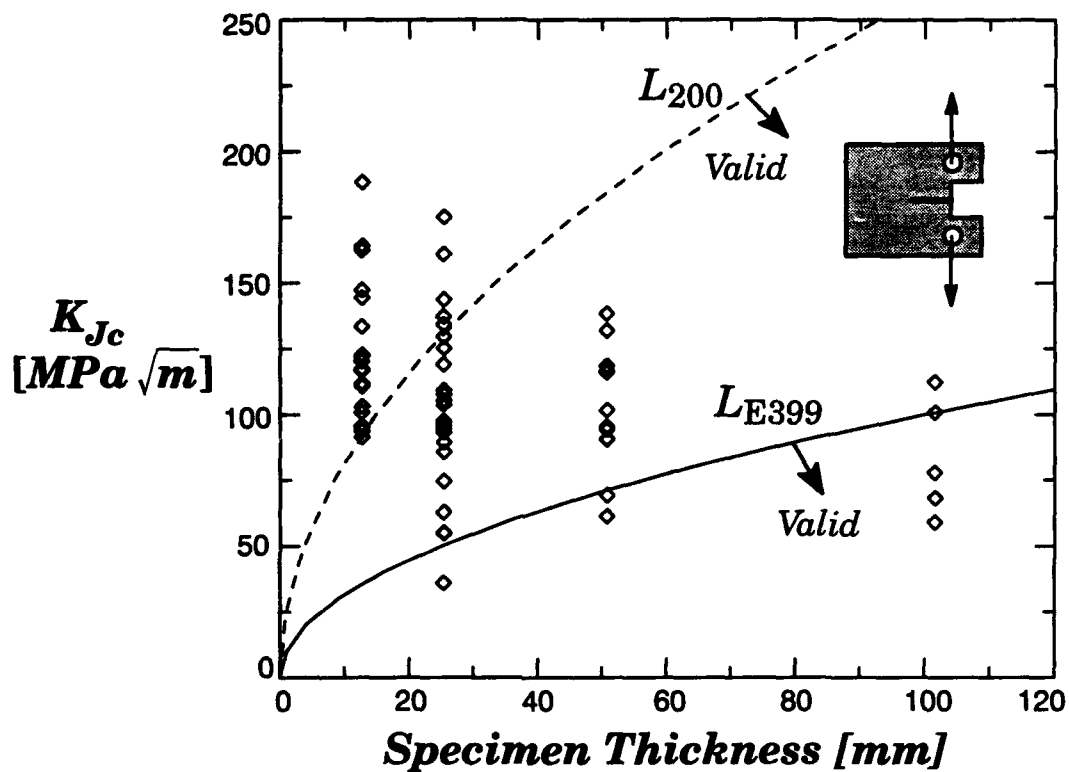


FIG. 6—Variation of fracture toughness with specimen thickness for A533-B at -75°C.

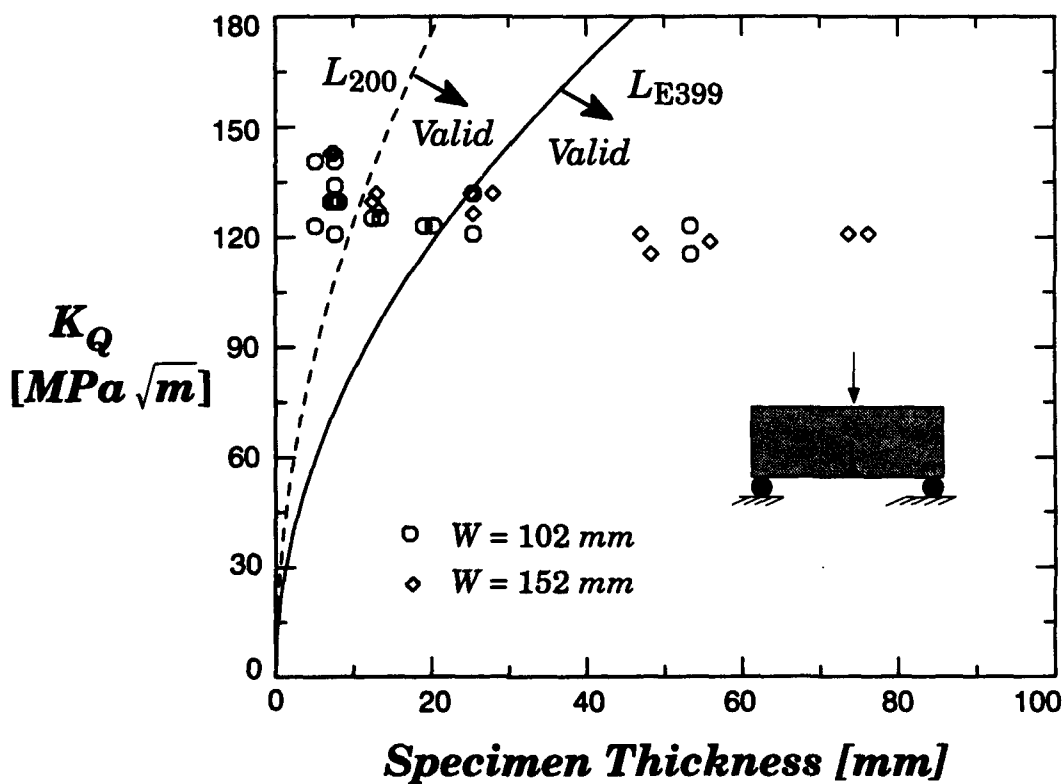


FIG. 7—Variation of fracture toughness with thickness for 18 Ni maraging steel.

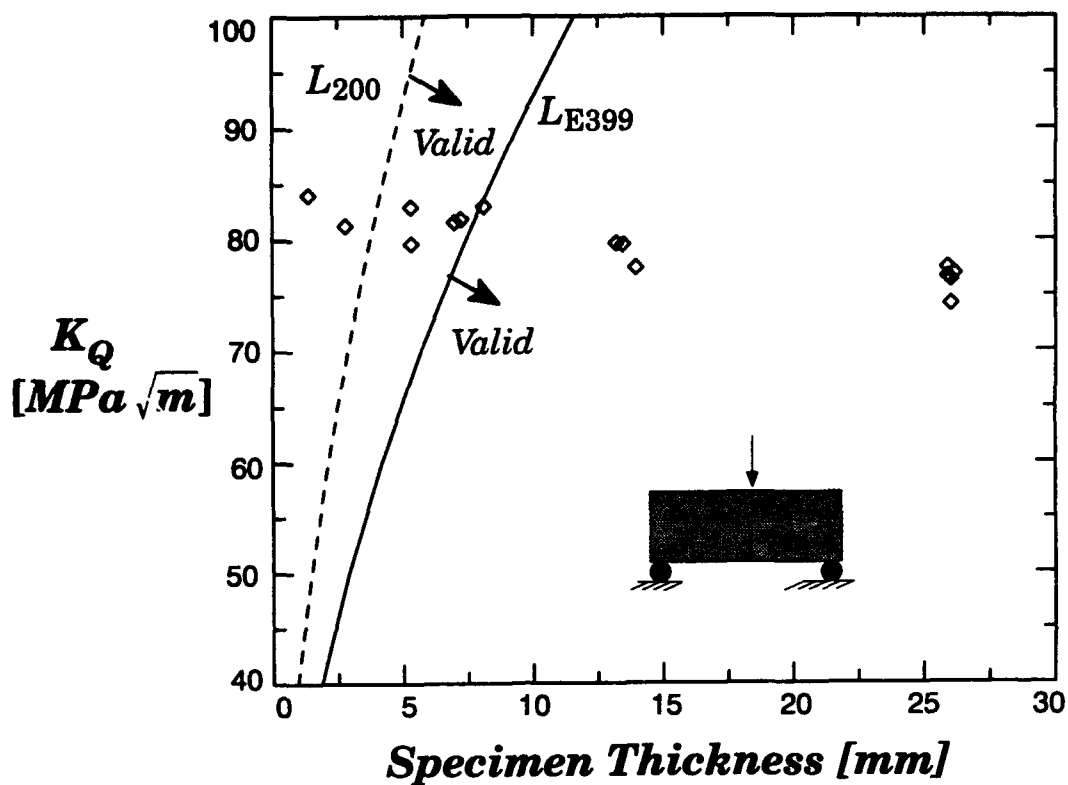


FIG. 8—Variation of fracture toughness with specimen thickness for 4340 steel $a_0 = 28$ mm, $W = 56$ mm.

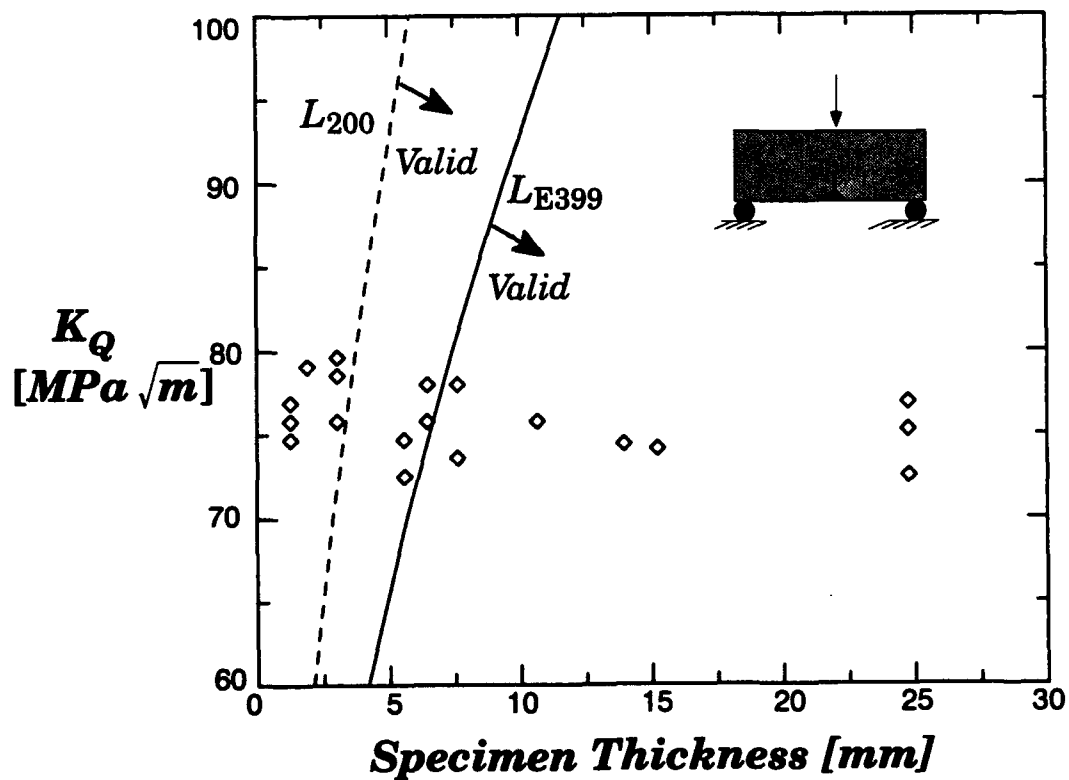


FIG. 9—Variation of fracture toughness with specimen thickness for 4340 steel $a_0 = 12.7$ mm, $W = 25.4$ mm.

11) shows a rapid increase in fracture toughness with decreasing thickness; this rapid upswing in toughness caused Jones and Brown [7] to argue (successfully) for the more restrictive 2.5 multiplier in the E399 size requirement. The proposed size limit includes only one additional data point beyond the E399 limit without allowing any specimen size dependent fracture toughness values.

5. SUMMARY AND DISCUSSION

This paper offers experimental verification of the DA size requirements for brittle fracture given in Eq (3). DA originally proposed these requirements for materials that fracture by transgranular cleavage. Subsequent development of the J - Q methodology generalizes the work of DA by removing the restriction of a stress-controlled, cleavage mechanism. The proposed size requirements are shown to quantify the limits under which conditions of small-scale yielding exist at the crack tip with both stress *and* strain fields uniquely characterized by J .

The proposed size requirements are examined for five existing data sets of fracture toughness which span properties between low strength-high modulus (A36) and high strength-low modulus (titanium). The proposed requirements successfully indicate toughness values in each data set which exhibit size dependency due to a loss of kinematic constraint against plastic deformation. The new size requirement is much less restrictive than the current E399 size requirement for materials with a low strength and high modulus, e.g., common structural and pressure vessel steels. For materials with a higher strength but lower modulus, e.g., the titanium alloy, the new requirement is just marginally less restrictive (the titanium alloy examined

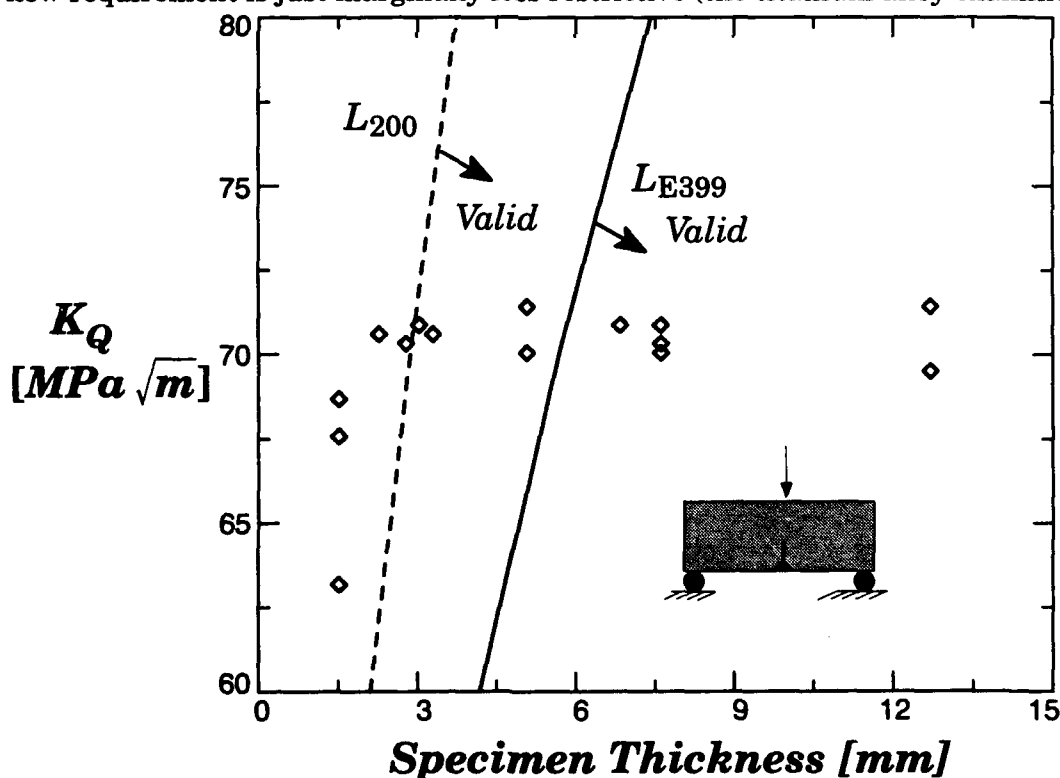


FIG. 10—Variation of fracture toughness with specimen thickness for 4340 steel, $a_0 = 6.9$ mm, $W = 14$ mm.

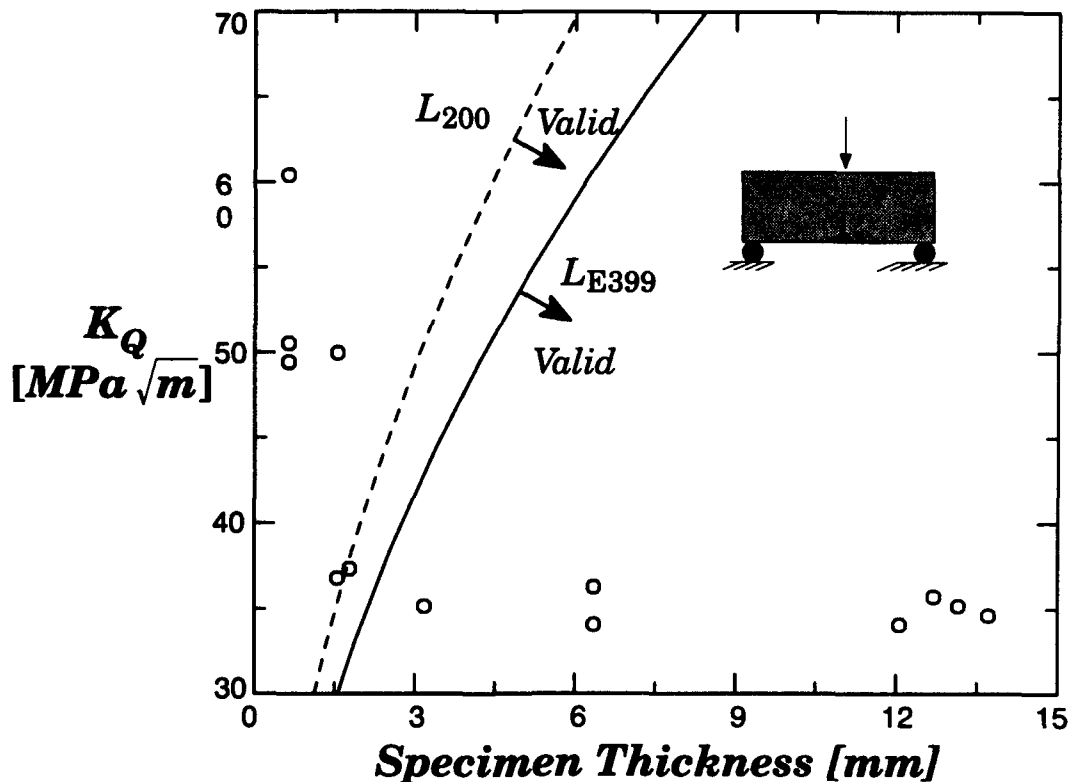


FIG. 11—Variation of fracture toughness with thickness for Ti 6Al-6V-2Sn.

here played a key role is setting the E399 factor of 2.5). By expressing the fracture toughness in terms of J , the strong influence of Young's modulus relative to strength is correctly reflected in the proposed size requirements.

On-going work by Dodds [3] suggests that the size requirements could be reduced to

$$a, b, B \geq \frac{100 J_c}{\sigma_0} \quad (15)$$

for certain deeply cracked SE(B) specimens of materials having a low yield strength and high Young's modulus which includes most structural and pressure vessel steels. Three-dimensional finite element analyses reveal that the centerplane of SE(B) specimens (with $B=W$) maintains small-scale yielding conditions at deformation levels greater than the plane-strain limit of Eq (3). Away from the centerplane, crack-tip conditions become less constrained which introduces the complexity of defining an "equivalent" thickness to quantify constraint levels. Nevertheless, it is clear that the proposed size requirement in Eq (3) is conservative for these materials and specimen geometries and that on-going work may provide sufficient justification to adopt Eq (15).

6. REFERENCES

- [1] Anderson, T. L. and Dodds, R. H., Jr., "Specimen Size Requirements for Fracture Toughness Testing in the Transition Region," *Journal of Testing and Evaluation*, JTEVA, Vol. 19, No. 2, March 1991, pp. 123-134.
- [2] Anderson, T. L. and Stienstra, D., "A Model to Predict the Sources and Magnitude of Scatter in Toughness Data in the Transition Region," *Journal of Testing and Evaluation*, JTEVA, Vol. 17, 1989, pp. 46-53.
- [3] Dodds, R. H., Jr., ASTM E08.08.04 meeting. Atlanta. (May, 1993)
- [4] Dodds, R. H., Anderson, T. L., and Kirk, M. T., "A Framework to Correlate a/W Ratio Effects on Elastic-Plastic Fracture Toughness (J_c)," *International Journal of Fracture*, Vol. 48, pp. 1-22, 1991.
- [5] Facuher, B. and Tyson, W. R. "A Study of Variability, Size, and Temperature Effects on the Fracture Toughness of an Arctic-Grade Steel Plate," *Fracture Mechanics: Eighteenth Symposium, ASTM STP 945*, D. T. Read and R. P. Reed, Eds., American Society for Testing and Materials, Philadelphia, 1988, pp. 164-178.
- [6] Hancock, J. W., Reuter, W. G., and Parks, D. M., "Constraint and Toughness Parameterized by T," *Constraint Effects in Fracture, ASTM STP 1171*, E. M. Hackett, K.-H. Schwalbe, and R. H. Dodds, Eds., American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 21-40, 1993.
- [7] Jones, M. H. and Brown, W. F., Jr., "The Influence of Crack Length and Thickness in Plane Strain Fracture Toughness Tests," *Review of Developments in Plane Strain Fracture Toughness Testing, ASTM STP 463* American Society for Testing and Materials, Philadelphia, 1970, pp. 63-101.
- [8] Larsson, S. G., and Carlsson, A. J., "Influence of Non-Singular Stress Terms and Specimen Geometry on Small-Scale Yielding at Crack Tips in Elastic-Plastic Materials," *Journal of Mechanics and Physics of Solids*, Vol. 21, 1973, pp. 263-278.
- [9] Lin, T., Evans, A. G., and Ritchie, R. O., "Statistical Model for Carbide Induced Brittle Fracture in Steel," *Journal of the Mechanics and Physics of Solids*, Vol. 34, 1986, pp. 477-496.
- [10] McCabe, D. E. "A Comparison of Weibull and β_{Ic} in Transition Range Data," *Fracture Mechanics: Twenty-Third National Symposium, ASTM STP 1189*, American Society of Testing and Materials, Philadelphia, 1993, pp. 80-94.
- [11] Narasimhan, R. and Rosakis, A. J., "Three Dimensional Effects Near a Crack Tip in a Ductile Three Point Bend Specimen - Part I: A Numerical Investigation," Report SM 88-6, California Institute of Technology, Division of Engineering and Applied Sciences, Pasadena, Calif., Jan. 1988
- [12] O'Dowd, N.P., and Shih, C.F., "Family of Crack-Tip Fields Characterized by a Triaxiality Parameter: Part I - Structure of Fields," *Journal of the Mechanics and Physics of Solids*, Vol. 39., No. 8, pp. 989-1015, 1991.
- [13] O'Dowd, N.P., and Shih, C.F., "Family of Crack-Tip Fields Characterized by a Triaxiality Parameter: Part II - Fracture Applications," *Journal of the Mechanics and Physics of Solids*, Vol. 40, pp. 939-963, 1992.
- [14] Ritchie, R. O., and Thompson, A. W., *Metallurgical Transactions A*, Vol. 16A, pp. 233-248, 1985.
- [15] Rolfe, S. T. and Novak, S. R., "Slow-Bend K_{Ic} Testing of Medium-Strength High-Toughness Steels," *Review of Developments in Plane Strain Fracture Toughness Testing, ASTM STP 463* American Society for Testing and Materials, Philadelphia, 1970, pp. 124-159.
- [16] Sorem, W. A., Dodds, R. H., and Rolfe, S. T., "Effects of Crack Depth on Elastic Plastic Fracture Toughness," *International Journal of Fracture*, Vol. 47, pp. 105-126, 1991.
- [17] Sumpter, J. D. G., and Forbes, A. T., "Constraint Based Analysis of Shallow Cracks in Mild Steel," *Proceedings of the International Conference on Shallow Crack Fracture Mechanics Tests and Applications*, TWI, Cambridge, England, September 1992.

- [18] Wallin, K., "The Effect of Ligament Size on Cleavage Fracture Toughness," *Engineering Fracture Mechanics*, Vol. 32, 1989, pp. 449–457.
- [19] Wallin, K., "Statistical Aspects of Constraint with Emphasis on Testing and Analysis of Laboratory Specimens in the Transition Region," *Constraint Effects in Fracture, ASTM STP 1171*, E. M. Hackett, K. H. Schwalbe, and R. H. Dodds, Eds., American Society of Testing and Materials, 1993, pp. 264–288.
- [20] Williams, M. L., *Journal of Applied Mechanics*, Vol. 24, pp. 109–114, 1957.

INITIAL DISTRIBUTION

OUTSIDE CENTER

Copies

1	DDRE/Lib	1	Brown Univ.
1	CNO/OP 098T	1	1 (Dr. C.F. Shih)
2	OCNR	1	Univ. of Illinois
	1 332 (Rajapakse)	1	1 (Dr. R.H. Dodds, Jr.)
	1 332 (Vasudivan)		
	1 0225	1	Texas A&M Univ.
	1 432S	1	1 (Dr. T.L. Anderson)
	1 Lib		
1	NAVPGSCOL	2	NASA/Langley
		1	Lib
		1	1 (Dr. J.C. Newman)
1	USNROTCU	1	Hibbit, Karlsson and Sorenson, Inc.
	NAVADMINU MIT		
2	NRL	1	University of Washington
	1 Code 6380	1	1 (Dr. A.S. Kobayashi)
	1 Code 6384		
8	NAVSEA	1	Univ. of Dayton Research Institute
	1 (SEA03M)	1	1 (J. Gallagher)
	1 (SEA03M2)		
	1 (SEA03P)		
	1 (SEA03P1)		
	1 (SEA03P2)		
	1 (SEA03P3)		
	2 (SEA08S)		
2	DTIC		
5	USNRC		
	1 (M. Mayfield)		
	2 (Dr. S.N. Malik)		
	1 (A. Hiser)		
	1 (Dr. E.M. Hackett)		
1	DOE, Oak Ridge		
2	NIST, Boulder		
	1 Lib		
	1 (J. Berger)		
4	NIST, Washington		
	1 Lib		
	1 (R. Fields)		
	1 (R. DeWitt)		
	1 (J.T. Fong)		

CENTER DISTRIBUTION

Copies

1	0115
1	60
1	60A
1	60D
1	601
1	602
1	603
1	65
2	65.4
1	66
2	66.3
1	68.
1	68.3
5	61
1	612
1	613
12	614
5	614 (R. Link)
1	615
1	3421
1	3422

NAVSESSES

1	62
1	624
1	625

REPORT DOCUMENTATION PAGE	1. REPORT NO. UILU-ENG-94-2002	2.	3. Recipient's Accession No.
4. Title and Subtitle Size and Deformation Limits to Maintain Constraint in K_{Ic} and J_c Testing of Bend Specimens			5. Report Date January 1994
7. Author(s) Kyle C. Koppenhoefer, Robert H. Dodds, Jr., Mark T. Kirk			8. Performing Organization Report No. SRS 586
9. Performing Organization Name and Address University of Illinois at Urbana-Champaign Department of Civil Engineering 205 N. Mathews Avenue Urbana, Illinois 61801			10. Project/Task/Work Unit No. 11. Contract(C) or Grant(G) No. N61533-90-K-0059 N00167-92-K-0038
12. Sponsoring Organization Name and Address Annapolis Detachment, Carderock Division Naval Surface Warfare Center CDNSWC 614 Annapolis, Maryland			13. Type of Report & Period Covered Interim: 1-1-93 to 12-31-93
15. Supplementary Notes			
16. Abstract (Limit: 200 words) <p>The ASTM Standard Test Method for <i>Plane-Strain Fracture Toughness of Metallic Materials</i> (E399-83) restricts test specimen dimensions to insure the measurement of highly constrained fracture toughness values (K_{Ic}). These requirements insure small-scale yielding conditions at fracture, and thereby the validity of linear elastic fracture mechanics. When these conditions are satisfied, the diameter of the plastic zone is nearly twenty five times smaller than all specimen dimensions. The need for this degree of plastic zone confinement, set by the factor 2.5 in $a, b, B \geq 2.5(K_{Ic}/\sigma_{ys})^2$, was based on K_{Ic} data for many different alloys. These data show that all specimens satisfying the size requirements of E399 produce highly constrained fracture toughness values. However, the required multiplier ranges from 1.0 for certain steel alloys to 2.5 for titanium alloy 6-6-2 in the aged condition. To maintain a standard test method applicable to all materials, the more restrictive 2.5 value has been retained by ASTM Committee E08. Recently, Dodds and Anderson have proposed a less restrictive size requirement for cleavage fracture toughness measured in terms of the J-integral (J_c). Dodds and Anderson performed finite element analyses to calculate the ratio of J in the finite-sized specimen ($J_{SE(B)}$) to J under small-scale yielding (J_{SSY}) needed to produce equivalent stresses ahead of both crack tips, and thereby equivalent conditions for cleavage fracture. The proposed size requirement specifies the deformation level at which $J_{SE(B)}/J_{SSY}$ deviates from unity for deeply cracked bend specimens, and is given by $a, b, B \geq 200 J_c/\sigma_0$. The size requirement proposed by Dodds and Anderson increases the utility of fracture toughness experiments by expanding the range of conditions over which such data can be reliably measured. This investigation compares the proposed size requirement with that of ASTM Standard Test Method E399 and, by comparison with published experimental data, provides validation of the new requirements.</p>			
17. Document Analysis a. Descriptors <p>Fracture toughness, specimen size requirements, experimental validation, J-integral</p> <p>b. Identifiers/Open-Ended Terms</p> <p>c. COSATI Field/Group</p>			
18. Availability Statement Release Unlimited		19. Security Class (This Report) UNCLASSIFIED 20. Security Class (This Page) UNCLASSIFIED	21. No. of Pages 15 22. Price